Gas Sensing Applications of Binary Metal Oxides: A Brief Review

Devendra Bhikaji Sonawane

Department of Physics, MGV's M.S.G. Arts, Science and Commerce College, Malegaon, Dist.- Nashik,
Affiliated to SPPU, Pune, and Maharashtra, India.
Corresponding author: swamidb1@gmail.com

Abstract

One of the challenges in metal oxide gas sensors is to achieve high sensitivity and selectivity towards specific gases of interest while minimizing cross-sensitivity to other gases present in the environment. This requires careful design and engineering of the sensor materials and operating parameters. Gas sensing applications of binary metal oxides have been an area of significant interest due to their high sensitivity, low cost, and stability. Binary metal oxides have shown promising results in detecting various reducing and oxidising gases, such as LPG, NH_4, CO, NOx, H_2S, and VOCs. These metal oxides exhibit semiconducting properties, and their conductance changes when exposed to different gases, enabling their use in gas sensing applications. The future prospects for gas sensing applications of binary metal oxides are promising, with ongoing research focused on enhancing their selectivity, sensitivity, response time, and stability. Integration with advanced technologies such as nanomaterials, nanocomposites, and functionalization with noble metals or other catalytic materials is expected to further improve the performance of binary metal oxide gas sensors. Additionally, the development of miniaturised and portable gas sensors for environmental monitoring, industrial safety, and healthcare applications is a growing area of interest. This review points out the shortcomings of the existing work on binary metal oxides. The main aim of the current review article is to provide brief information on applications and methods of preparation of binary metal oxides.

Keywords: binary metal oxides, noble metals, gas sensing, nanomaterials, environmental monitoring.

1. Introduction

Air pollution poses significant threats to both human health and the environment [1]. It results from the release of various pollutants, such as particulate matter, carbon monoxide, sulfur dioxide, and nitrogen dioxide, into the atmosphere. These pollutants can cause respiratory issues, heart diseases, and even premature death in humans [1, 2]. Moreover, air pollution contributes to climate change, acid rain, and the depletion of the ozone layer, which in turn affects ecosystems, agriculture, and wildlife. To mitigate these impacts, it is crucial to implement stricter emission standards, promote clean energy, and encourage responsible practices in industries and households [3, 4]. Gas sensors play a crucial role in addressing several vital needs across various sectors, driven by the growing emphasis on safety, environmental monitoring, and industrial processes [5, 6]. In industrial area, gas sensors are essential for monitoring and detecting hazardous gases, such as hydrogen sulfide, carbon monoxide, ammonia, and volatile organic compounds. Early detection and alarm systems based on gas sensors are critical for ensuring the safety of workers and preventing potential gas-related accidents. Gas sensors are employed for environmental monitoring in both indoor and outdoor environments. They are used to detect and measure levels of pollutants, including carbon dioxide, nitrogen oxides, sulfur dioxide, and volatile organic compounds, to assess air quality and ensure compliance with environmental regulations [7, 8]. The need for gas sensors is evident in protecting human health, ensuring workplace safety, meeting environmental regulations, and enhancing the efficiency of industrial processes [8, 9].

Metal oxide gas sensors have garnered significant attention for their diverse applications in gas detection and environmental monitoring [10]. These sensors utilize the semiconducting properties of metal oxides to detect and quantify the presence of specific gases. Metal oxides are utilized in gas sensing applications for detecting harmful gases such as carbon monoxide, nitrogen oxides, and volatile organic compounds. Their semiconducting properties enable the development of gas sensors for environmental monitoring, industrial safety, and automotive applications [10, 11]. Metal oxide gas sensors operate based on the principle of changes in electrical conductivity when exposed to target gases. Adsorption of gas molecules on the surface of the metal oxide alters its conductivity, leading to a measurable change in resistance. This change is then correlated to the concentration of the target gas [11].

Binary metal oxide (BMO) gas sensors refer to a specific type of gas sensor that utilizes a combination of two different metal oxide materials as the sensing element [12]. These sensors are primarily used for detecting and analyzing various gases in the environment. In a binary metal oxide gas sensor, the two metal oxides are mixed together, creating a heterogeneous mixture. This combination aims to improve the overall performance of the sensor by exploiting the synergistic effects between the two metal oxides [12, 13]. These effects can lead to enhanced selectivity, sensitivity, and stability in detecting specific target gases. The combination of these materials can result in improved gas sensing capabilities, making binary metal oxide gas sensors a valuable tool in various industries, such as environmental monitoring, industrial safety, and air quality control [13, 14]. The inadequacies of the previous research on binary metal oxides are highlighted in this study. The primary goal of this present article is to give a quick overview of the uses and preparation techniques for binary metal oxides.

2. Synthesis methods for Binary Metal Oxide gas sensors

The binary metal oxides are synthesised using various methods such as physical, chemical and biological [15-17]. Many methods are reported for the preparation or synthesis of binary metal oxide gas sensors. Fig. 1 reveals the methods adopted for synthesis of binary metal oxides for application of gas sensors.

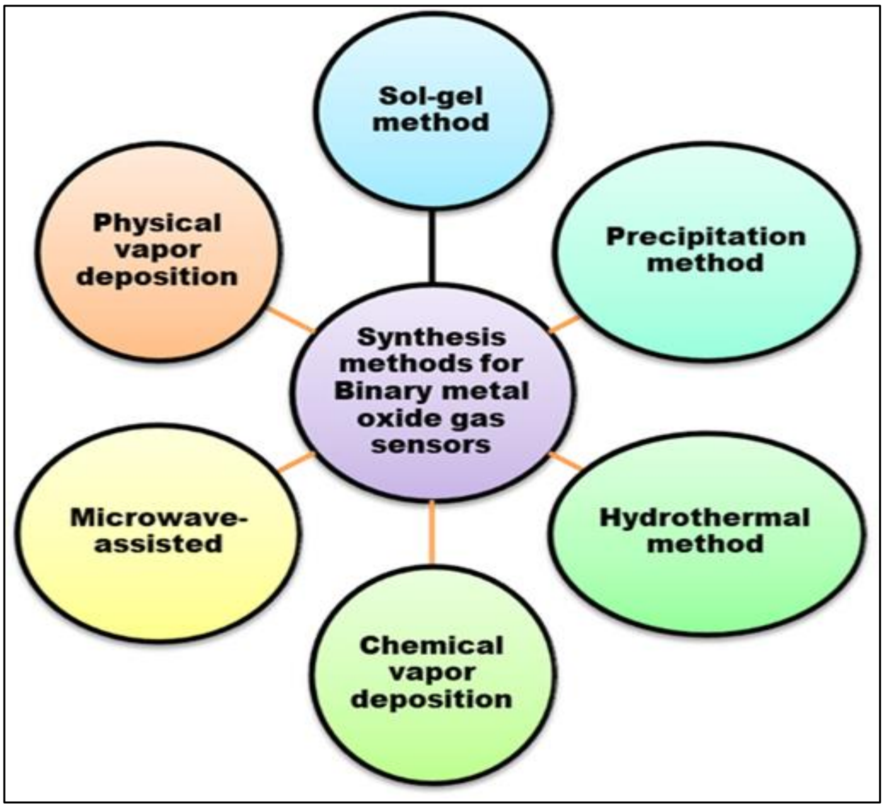

Figure 1: Synthesis methods of binary metal oxide gas sensors

2.1 Sol-gel method: This technique involves the formation of a sol (a colloidal suspension) by mixing metal alkoxides or metal salts with a solvent. The sol is then transformed into a gel through a hydrolysis and condensation process. The gel is dried and calcined at high temperatures to obtain the desired binary metal oxide. The sol-gel method allows for precise control over the composition, morphology, and particle size of the final product [18, 19].

2.2 Co-precipitation method: In this method, metal salts are dissolved in a solution containing a precipitating agent, such as ammonia or sodium hydroxide. The reaction between the metal ions and the precipitating agent leads to the formation of a binary metal oxide precipitate. The precipitate is then washed, dried, and calcined to obtain the final product. This method is suitable for producing binary metal oxides with a wide range of compositions [19, 20].

2.3 Hydrothermal and solvothermal synthesis: These methods involve the reaction of metal precursors in a high-temperature, high-pressure aqueous or non-aqueous solution, respectively. The reaction takes place in a closed, temperature-controlled autoclave. The binary metal oxide product forms as a result of the controlled crystallization process. Hydrothermal and solvothermal synthesis can produce binary metal oxides with well-defined structures and controlled particle sizes [21, 22].

2.4 Chemical vapor deposition (CVD): These techniques involve the deposition of binary metal oxide thin films on a substrate by introducing metal precursors in the gas phase. CVD uses chemical reactions between the precursors and the substrate [21].

2.5 Physical vapor deposition (PVD): PVD relies on physical processes like sputtering or evaporation. These methods are suitable for producing thin-film binary metal oxide gas sensors with controlled thickness and composition [22].

2.6 Microwave-assisted synthesis: In this method, binary metal oxide materials are synthesized using microwave radiation as the heat source. Microwave-assisted synthesis can lead to rapid and uniform heating of the reaction mixture, resulting in shorter synthesis times and improved control over the final product's properties [22, 23].

3. Factors affecting the gas sensing performance of the binary metal oxide gas sensors

Several factors influence the gas sensing performance of binary metal oxide gas sensors. These factors can affect the sensitivity, selectivity, response time, and stability of the sensors [24]. Some key factors are shown in Fig. 2.

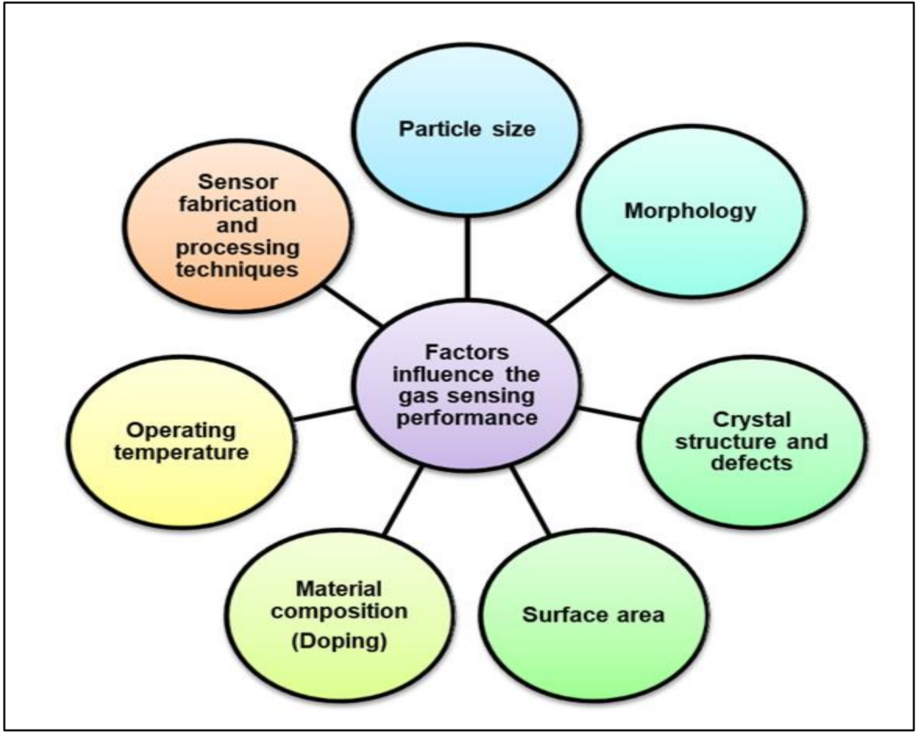

Figure 2: Factors influence the gas sensing performance of binary metal oxide gas sensors

3.1 Material composition: The choice of metal oxides and their proportions in the binary mixture play a significant role in determining the gas sensing properties. The combination of two metal oxides can lead to synergistic effects, which can improve the overall performance of the sensor.

3.2 Particle size and morphology: The size and shape of the binary metal oxide particles can impact the sensor's response to target gases. Smaller particles typically exhibit higher surface area, leading to increased sensitivity. Additionally, the morphology of the particles can affect the gas diffusion and adsorption process, which in turn influences the sensor's performance.

3.3 Surface area: A higher surface area allows for more active sites on the sensor's surface, resulting in improved sensitivity to target gases. The surface area can be influenced by factors such as particle size, porosity, and agglomeration.

3.4 Crystal structure and defects: The crystal structure and the presence of defects within the binary metal oxide material can impact the gas sensing properties. Defects can act as active sites for gas adsorption and interaction, which can enhance the sensor's sensitivity and selectivity.

3.5 Operating temperature: The temperature at which the sensor operates can significantly affect its performance. Higher temperatures generally lead to increased sensitivity and response speed, but they can also cause sensor degradation over time. Optimizing the operating temperature is crucial for achieving the best gas sensing performance.

3.6 Sensor fabrication and processing techniques: The methods used for synthesizing and processing the binary metal oxide material can influence the gas sensing properties. Factors such as the presence of impurities, grain size, and the uniformity of the film or particle distribution can impact the sensor's performance.

3.7 Gas concentration and humidity: The concentration of the target gas and the presence of humidity in the environment can affect the sensor's response. Some binary metal oxide sensors may be more sensitive to humidity, leading to potential cross-sensitivity and interference in the gas detection process.

3.8 Sensor design and integration: The design of the sensor, including the choice of transducer and the integration of the binary metal oxide layer, can also impact its gas sensing performance. Proper design and integration can help optimize the sensor's sensitivity, selectivity, response time, and stability.

4. Literature Survey:

In 1953, Brattain and Bardeen conducted the first research of the semiconductor material group on germanium (Ge). Heiland's research report on metal oxides' gas sensitivities was published in 1954. Seiyama's work from 1962 demonstrated that ZnO structures were susceptible to airborne reactive gases [24]. 1968 saw the introduction of Taguchi-type sensors to the marketplace and the industrialization of tin oxide gas sensors. Presently, real-time gas sensors that use chemiresistive metal oxide semiconductors have become increasingly important in both science and industry because of their high sensitivity to chemical environments, affordability, ease of implantation, safety, and durability at high temperatures and high pressures all of which indicate compelling conditions [25, 26]. One major issue with metal oxide gas sensors is gas selectivity. In recent investigations, it has been suggested to adopt a heating mode of a gas-sensing floor with continuous temperature modification to boost the selectivity of metal oxide sensors. Researchers stated that, by choosing the metal oxide material to have specific surface properties that enhance selectivity to the target gas [28, 29]. This can involve modifying the metal oxide composition or doping it with other elements. Also modifying the surface of the metal oxide with functional groups or coatings that selectively interact with the target gas [29, 30]. This can enhance the sensitivity and selectivity of the sensor. Adjusting the operating conditions such as temperature, humidity, and gas flow rate can improve the selectivity of the sensor to specific gases. Implementing these strategies can help mitigate the gas selectivity problem in metal oxide semiconductor gas sensors, improving their accuracy and reliability in gas detection applications [30, 31]. Hence now a days researchers are focused on the work on binary metal oxides sensors because binary metal oxides are exhibit tunable properties based on the composition ratio of the two metals. This allows for fine-tuning of the sensor's response to specific gases, improving selectivity. The combination of two different metal oxides can result in synergistic effects, where the properties of the binary oxide are different from the individual components [32, 33]. This can lead to improved sensitivity and selectivity. It offer a promising avenue for enhancing the sensitivity and selectivity of gas sensors, making them valuable for various industrial, environmental, and healthcare applications.

5. Conclusion and future scope

Binary metal oxides, are compounds composed of two different metal cations bonded to oxygen, have garnered significant interest due to their diverse properties and potential applications. Drawing conclusions about these materials involves considering their current applications, ongoing research trends, and potential future directions. BMO hold great promise for a wide range of applications, and ongoing research efforts aimed at understanding their properties and behavior will likely lead to further advancements and practical implementations in various fields. Efforts to integrate BMO into practical devices, such as batteries, sensors, and catalytic reactors, will drive their commercialization and real-world impact.

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